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NUMERICAL SIMULATION OF WAVE ATTACK ON SEA DIKE WITH ASPHALT CONCRETE REVETMENT

***Issam Jassim[1], Shuhong Tan[2], Pieter A. Vermeer[1, 3] and Michael A. Hicks[2, 3]**

[1]Institute of Geotechnics, Stuttgart University, Pfaffenwaldring 35D, 70569, Stuttgart, Germany
[2]Geo-engineering Section, CITG, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, The Netherlands
[3]Deltares, Stieltjesweg 2, 2628 CK, Delft, The Netherlands

*issam.jassim@igs.uni-stuttgart.de

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ABSTRACT

The numerical simulation of wave attack on a sea dike with an asphalt concrete revetment during a severe storm is carried out using the dynamic Finite Element Method. When wave loads attack the revetment during such a storm, both the revetment and the underlying soil may be damaged. The two-phase flow equations are considered, to study the dynamic generation and dissipation of excess pore pressures in the saturated soil underneath the revetment caused by the cyclic wave attack. Moreover, a sensitivity study for the revetment is presented to indicate the importance of the stiffness of the concrete.

1 INTRODUCTION

Approximately 30 percent of the Netherlands lies below sea level, which makes flood defence very important. Currently, more than 400 kilometres of Dutch sea dikes have an asphalt revetment. It is used to protect the soil under it against failure and erosion due to wave attack. Most of the revetments have a thickness of 20 to 30 cm in the wave attack zone. In this study, wave attack on a sea dike with an asphalt revetment is simulated by the dynamic Finite Element Method.

Considering the nearly saturated soil in the sea dike, the calculation in this article was done using the equations of two-phase flow developed by Vermeer et al. (2011). The wave attack on the sea dike causes problems associated with the significant dynamic generation and dissipation of excess pore pressure. The paper will demonstrate the process of generation and dissipation of the pore pressures and the deformations of the revetment under the wave attack.

2 METHODOLOGY

Considering the process of the saturated soil under dynamic wave loading, the equilibrium equation for the momentum of the soil-water mixture can be written as:

$$\mathbf{M}_s \dot{\mathbf{v}} + \mathbf{M}_{w,n} \dot{\mathbf{w}} = \mathbf{F}^{ext} - \mathbf{F}^{int} \tag{1}$$

where $\mathbf{v}$ is the velocity of the soil skeleton, $\mathbf{w}$ is the velocity of the water, $\mathbf{M}_s$ is the mass matrix of the soil skeleton and $\mathbf{M}_{w,n}$ is the mass matrix of the pore water, which are defined as:

$$\mathbf{M}_s = \int_V (1-n)\rho_s \mathbf{N}^{\mathrm{T}}\mathbf{N} dV, \quad \mathbf{M}_{w,n} = \int_V n\rho_w \mathbf{N}^{\mathrm{T}}\mathbf{N} dV \tag{2}$$

where n is the porosity of the soil, ρ_s is the density of soil grains, ρ_w is the water density, $\mathbf{N}$ are the shape functions, $\mathbf{F}^{ext}$ are the external forces, including the external traction and body forces acting on the mixture, and $\mathbf{F}^{int}$ are the internal forces coming from the effective stresses and the pore pressure. They are given by:

$$\mathbf{F}^{ext} = \int_V (1-n)\rho_s \mathbf{N}^{\mathrm{T}}\mathbf{g}\; dV + \int_V n\rho_w \mathbf{N}^{\mathrm{T}}\mathbf{g}\; dV + \int_S \mathbf{N}^{\mathrm{T}}(\mathbf{t}' + \mathbf{n}\tilde{p})\; dS \tag{3}$$

$$\mathbf{F}^{int} = \int \mathbf{B}^{\mathrm{T}}(\boldsymbol{\sigma}' + \mathbf{I}p)\, dV \tag{4}$$

where **g** is the vector of gravitational acceleration, **t′** and $\tilde{p}$ are the surface tractions applied to the soil skeleton and water, respectively, **B** are the shape function derivatives, **σ′** is the effective stress in Voigt vector form, *p* is the pore water pressure, **n** is the surface normal vector given by [n_1, n_2, n_3] and **I** is a vector defined as $\mathbf{I} = [1, 1, 1, 0, 0, 0]^{\mathrm{T}}$.

A similar equation can be written for the equilibrium of the momentum of the water:

$$\mathbf{M}_w \dot{\mathbf{w}} + \mathbf{Q}(\mathbf{w} - \mathbf{v}) = \mathbf{F}_w^{ext} - \mathbf{F}_w^{int} \tag{5}$$

in which $\mathbf{M}_w$ is the mass matrix of the water and **Q** corresponds to the interaction between the solid and water. They are defined as:

$$\mathbf{M}_w = \int_V \rho_w \mathbf{N}^{\mathrm{T}} \mathbf{N} dV, \quad \mathbf{Q} = \int \frac{n\mathbf{N}^T \mathbf{N} \rho_w g}{k} dV \tag{6}$$

where *k* is the hydraulic conductivity. As found by Van Esch et al. (2011), this two-phase formulation correctly captures the response to dynamic loading for saturated soil, because the acceleration of the water phase $\dot{\mathbf{w}}$ is taken into account.

3 BACKGROUND OF THE DUTCH SEA DIKE

Asphalt revetments in the Netherlands are usually designed to withstand a storm which may happen every 4000 years. For design purposes, the duration of this “super storm” is taken to be 35 hours. During this period, the revetment is severely and cyclically loaded by wave attack. The position of the impact point is defined as the location of the highest impact pressure that occurs per wave attack. The impact points of most waves tend to lie below the Still Water Level (CIRIA, 2010). The SWL during the storm is the summation of the usual tidal SWL and the wind setup. Due to the so-called wind setup, both the low and high tide levels increase. In the Netherlands a typical value for the wind setup is 3.50 m.

The waves of the North Sea between England and the Netherlands have a typical period of 5 s to 10 s. However, the impact period of a breaking wave on the dike revetment has a much shorter duration of about 0.1 s. In the present analyses, a wave period of 10 s is assumed and the wave attack duration is taken to be 0.1 s. According to De Looff et al. (2006), the load intensity of a breaking wave is inversely proportional to the tangent of the slope angle. Considering a slope angle of 1:4, a maximum wave impact pressure of 240 kPa is assumed, as indicated in Figure 1a. This corresponds to a severe wave attack during a storm with a significant wave height of 4 m. The distribution of the wave load is assumed to be triangular with a width of 2 m, as shown in Figure 1b.

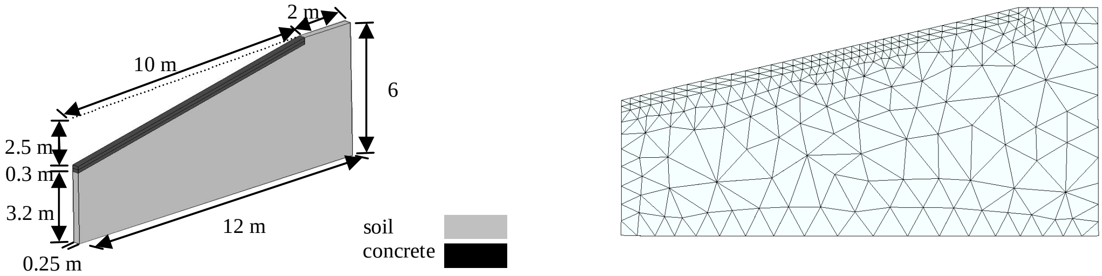
4 NUMERICAL MODEL OF SEA DIKE

Figure 2a shows the modelled three-dimensional geometry of the dike, with a 30 cm thick layer of concrete placed on the sloping surface of the dike. The slope inclination is assumed to be 1:4. In this simulation, only a thin slice of width 0.25 m is considered, to represent the analysis of a plane strain problem by using four-node tetrahedral elements. A side view of the 3D mesh is shown in Figure 2b. The mesh comprises 1457 elements.

(a) Wave load of Haversine time distribution

(b) Simplified wave shape

Fig. 1 Distribution of wave load



(a) Geometry of the sea dike (b) Side view of the 3D mesh

Fig. 2 Geometry of the sea dike and 3D mesh with plane strain boundary conditions

The soil is modelled using the Mohr-Coulomb model with a Young's modulus of 10 MPa, Poisson's ratio of 0.33, cohesion of 1 kPa, friction angle of 35° and saturated mass density of 2000 kg/m^3. A hydraulic conductivity of 10^{-4} m/s is assumed in this study, which is typical for sand. The porosity is taken to be 0.4. By assuming the degree of saturation of the soil to be 0.99, the bulk modulus of the pore water is estimated as 10 MPa.

The concrete is modelled as a linear elastic material, with a Poisson's ratio of 0.3 and a mass density of 2400 kg/m^3. A realistic elastic stiffness for concrete, for loading at relatively low temperature and very short pulses, would be in the range of 1 to 10 GPa. However, the precise stiffness depends also on the age and quality of the revetment. For this reason, it is decided to perform a sensitivity study with different stiffnesses equal to 20 MPa, 1 GPa and 10 GPa for the concrete.

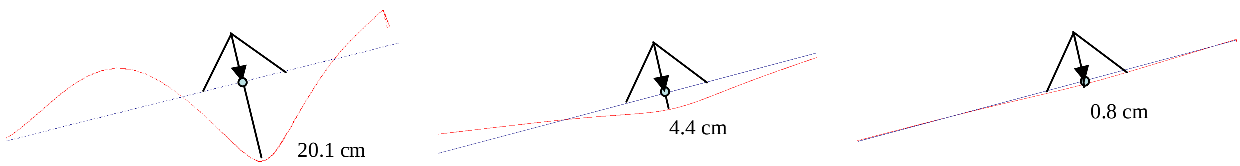
The ground water table below the revetment is taken to be equal to the outside SWL. This implies that both above and below the revetment the quasi-static part of the (pore) water pressure is equal. The latter simplifies the analysis, as both the weights of the revetment and the saturated soil are considered to be submerged.

5 NUMERICAL RESULTS

The numerical model is simulated using the dynamic Finite Element Method with the two-phase flow equations. The simulation consists of two calculation phases. The first phase is the gravity phase with quasi-static loading; there is no pore pressure generated during this phase. The second phase is the dynamic load phase with fully dynamic application of the wave attack, which leads to the generation and dissipation of the excess pore pressures.

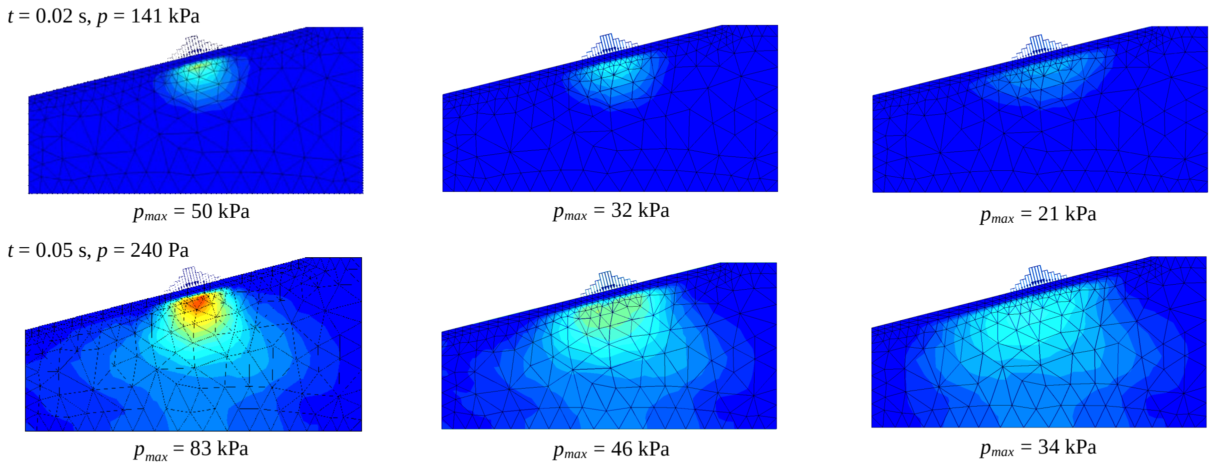
When experiencing cyclic wave loading during a storm, there will be settlements experienced by both the revetment and the soil. Computational results for the displacements of the revetment when applying the peak load of the 10th cycle are shown in Figure 3. Obviously, the displacement at the impact point differs considerably for the three concrete stiffnesses of 20 MPa, 1 GPa and 10 GPa. The calculation with the lowest revetment stiffness shows much larger deformations, indicating the importance of a high quality revetment.

Figure 4 shows the excess pore pressures for the three different stiffnesses, at times of 0.02 s and 0.05 s of the 10th cycle. At time t = 0.02 s, before the peak load, the maximum wave load intensity is 141 kPa. The resulting maximum excess pore pressures directly under the impact point are 50 kPa, 32 kPa and 21 kPa for the three different moduli of the concrete. At t = 0.05 s, when the peak wave load of 240 kPa is reached, the maximum excess pore pressures are 83 kPa, 46 kPa and 34 kPa respectively. Hence, the maximum excess pore pressures reach 35%, 20% and 15% of the maximum load intensity respectively.



(a) $E_{concrete}$ = 20 MPa (b) $E_{concrete}$ = 1 GPa (c) $E_{concrete}$ = 10 GPa

Fig. 3 Displacements at the surface of the concrete for the 10th loading cycle



(a) $E_{concrete}$ = 20 MPa (b) $E_{concrete}$ = 1 GPa (c) $E_{concrete}$ = 10 GPa

Fig. 4 Contours of excess pore pressure for different stiffnesses of concrete

This effect is mainly the result of load spreading due the stiffness of the revetment. It means that, the stiffer the concrete, the smaller the excess pore pressures, but the larger the zone where excess pore pressures develop.

Another reason for the relatively low excess pore pressures comes from the slightly compressible pore water, due to the incomplete saturation. Indeed, on assuming 0.99 for the degree of the saturation, the bulk modulus of the pore water is found to be 10 MPa, which is equal to the Young's modulus of the soil skeleton. As a consequence, the load is not carried only by the pore water, but also by the effective stresses.

6 CONCLUSION

The dike problem, with coupling between the pore pressures and deformations under dynamic loading, is considered in the present study using the Finite Element Method. A sensitivity study of the revetment is done by comparing the numerical results for different values of the stiffness of the concrete, with all results implying the importance of a high quality revetment. The computed results for the dynamic generation and dissipation of excess pore pressures are in good agreement with reality, indicating that the two-phase flow equations work well for the saturated soil under dynamic loading.

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References

[1] P.G. Bonnier. *Testing, modelling and numerical analysis of the mechanical behaviour of bituminous concrete*. Ph.D. Thesis, Delft University of Technology, Delft, the Netherlands, 1993.

[2] CIRIA. *The beach management manual*, 2010.

[3] A.K. de Looff, R.'t Hart, K. Montauban and M. van de Ven. Golfklap a model to determine the impact of waves on dike structures with an asphaltic concrete layer. *Coastal Engineering*, 2006; 5106-5115.

[4] J. van Esch, D. Stolle and I. Jassim. Finite element method for coupled dynamic flow-deformation simulation. *Proceedings of the 2nd International Symposium on Computational Geomechanics (COMGEO II)*, Cavtat-Dubrovnik, Croatia, 2011; 415-524.

[5] P.A. Vermeer, I. Jassim and S. Tan. New horizons in numerical analysis for geotechnical engineering. *Proceedings of the International Conference Geotec Hanoi, Geotechnics for Sustainable Development*, Hanoi, Vietnam, 2011; 723-732.